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Comparison of inclusive particle production in 14.6 GeV/c proton-nucleus collisions with simulation

D. E. Jaffe [b], K. H. Lo [c], J. R. Comfort [a], and M. Sivertz [b]

[a] *Arizona State University, Dept. of Physics and Astronomy, Tempe, AZ*

[b] *Brookhaven National Laboratory, Upton, NY*

[c] *Stony Brook University, Dept. of Physics and Astronomy, Stony Brook, NY*

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Abstract

Inclusive charged pion, kaon, proton, and deuteron production in 14.6 GeV/c proton-nucleus collisions measured by BNL experiment E802 is compared with results from the GEANT3, GEANT4, and FLUKA simulation packages. The FLUKA package is found to have the best overall agreement.

Key words: simulation, Monte Carlo, inclusive production, proton-nucleus collisions
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1 Introduction

The simulation of particle production in proton-nucleus collisions is important for a number of ongoing and future high energy physics experiments. Interpretation of atmospheric neutrino data requires knowledge of hadronic interactions on light nuclei for lab energies from 1 to 10^5 GeV [1]. The design of secondary beams for the study of neutrino interactions [2] or rare kaon decay [3] relies on the accurate simulation of proton-nucleus collisions at energies in the range 10-100 GeV. In addition, validation of simulations in accessible energy regions is important for the interpretation of LHC data [4].

In this paper we compare the data of BNL experiment E802 [5] with simulated results of the GEANT3 [6], GEANT4 [7], and FLUKA [8] packages. Experiment E802 measured $\pi^{\pm}$, $K^{\pm}$, proton, and deuteron production in the angular range 5° to 58° in collisions of 14.6 GeV/c protons with Be, Al, Cu,

and Au targets. The E802 magnetic spectrometer had a geometrical solid angle acceptance of 25 msr and was rotated to take data at five overlapping angular settings. Particle identification was accomplished with time-of-flight and a gas Cherenkov detector. The measured spectra were presented as invariant cross sections $\frac{d^2\sigma}{2\pi m_t dm_t dy}$ as a function of transverse kinetic energy $(m_t - m_0)c^2 = \sqrt{(m_0c^2)^2 + (p_\perp c)^2} - m_0c^2$ in bins of rapidity where m_0 is the particle mass. The overall uncertainty in the cross section normalization is estimated to be $\pm(10 - 15)\%$.

The E802 results have previously been compared to simulation. The JAM1.0 hadronic cascade model [9] showed good agreement with the measured proton, $\pi^\pm$, and $K^\pm$ spectra for all four targets as a function of $m_t - m_0$ and rapidity. The p-Be data as a function of rapidity has been compared with FLUKA [10] in the calculation of atmospheric neutrino flux. The agreement is reasonable with the largest deviation being a factor ~ 1.2 (~ 2) for the pion (kaon) spectra. Several simulation models were compared with the p-Be data as a function of $m_t - m_0$ and rapidity in the framework of the CORSIKA program [11]. Pion production in FLUKA 2002 and UrQMD 1.3 [12] had the same slope as function of $m_t - m_0$ as the data over the whole rapidity range, while the GHEISHA 2002 [14], QGSJET 01 [15], and neXus 3 [13] models were unable to reproduce the slope as a function of $m_t - m_0$ over the full kinematic range of the data.

2 Simulation packages

In this paper for the GEANT3 simulation we used the hadronic simulation package GCALOR version 1.05/03 [16] with GEANT version 3.21, for the GEANT4 simulation we used GEANT version 4.7.1 and simulation packages ("physics lists") QGSP, QGSC, QGSP_BIC, and QGSC_LEAD_HP [17], and we used version 2005.6 of FLUKA. The GEANT4 physics list QGSP employs a "quark gluon string model... and a pre-equilibrium decay model with an extensive evaporation phase to model the subsequent nuclear fragmentation" and is recommended [17] for medium energy (15-50 GeV) protons on light targets. QGSC is similar to QGSP for the initial reaction and " ...uses chiral invariant phase-space decay ... to model the behavior of the system's fragmentation." QGSP_BIC is similar to QGSP but uses the binary cascade for nucleon interactions below 3 GeV. QGSC and QGSP_BIC are recommended physics lists for high energy applications. The physics list QGSC_LEAD_HP is recommended for the calculation of LHC detector neutron fluxes.

We simulated 14.6 GeV/c proton interactions on Be, Al, Cu, and Au targets of thickness 1478 mg/cm^2, 1620 mg/cm^2, 1434 mg/cm^2, and 1000 mg/cm^2,

respectively. The kinematics of charged pions, kaons, protons, and deuterons at a radius of 25 cm from the interaction point were recorded. The lifetime of the charged mesons was artificially set to be infinite to avoid performing a decay-in-flight correction to the measured yields. For each target and model we generated 50 million incident protons. No importance weighting or event biasing was used and the uncertainty in the evaluated cross sections is based on the statistics of the generated events only.

3 Comparison with E802 data

The data and simulation results for the invariant cross-sections are shown in Figures 1, 2, 3, 4, 5, and 6 for the four targets for π^+, π^-, K^+, K^-, p, and d data, respectively. Only the QGSC GEANT4 results are shown for the $\pi^\pm$, $K^\pm$, and p data as the four GEANT4 simulation packages give nearly identical results. The statistical uncertainties in the results from simulation are similar for all models and are only shown for the QGSC package to aid comparison with the statistical uncertainties in the data. For the deuteron data, only the packages that give non-zero cross sections for $y > 0.4$ are shown in Figure 6. The ratios of Monte Carlo results to data are shown in Figures 7, 8, 9, 10, and 11 for all four targets for π^+, π^-, K^+, K^-, and p, respectively. The ratios are not shown for the deuteron data given the sparse nature and obviously poor agreement with the simulation. There is no significant difference in the ratios for $\pi^\pm$, $K^\pm$ and p production for the four GEANT4 models except for QGSC and QGSP for the heaviest target; accordingly we show only the QGSC prediction except for the gold target. The predictions for the QGSP, QGSP_BIC, and QGSC_LEAD_HP models are statistically consistent for all targets. The statistical uncertainty in the data and the Monte Carlo are combined in quadrature to produce the uncertainty in the ratios shown in the Figures while the E802 normalization uncertainty is indicated separately.

As seen in Figure 7 for π^+ production, FLUKA generally has good agreement in slope but overestimates the magnitude by up to a factor of two at low rapidity. All the GEANT4 packages give similar results and agree in magnitude with the data at lowest m_t but do not agree in slope for $y < 1.4$, 1.6, 1.6, and 1.8 for the Be, Al, Cu, and Au targets, respectively. GCALOR has better agreement than FLUKA or GEANT4 for the π^+ data.

Similar observations can be made for π^- production in Figure 8. GCALOR most accurately reproduces the data over the measured kinematic range with some underestimate of the magnitude at low m_t and high rapidity. FLUKA has reasonable agreement in slope and is within a factor of two in magnitude for all the data. The GEANT4 agreement is good for all the Be data and

agrees for the heavier targets at low m_{t} or $y > 1.2$, 1.6, and 1.6 for Al, Cu, and Au, respectively.

For positive kaon production (Figure 9), FLUKA agrees in slope and magnitude for the Al, Cu, and Au targets. For the Be target, FLUKA agrees in slope but the magnitude is higher than the data. The GCALOR agreement with the data is comparable to FLUKA for the Be target, but consistently underestimates the magnitude for the heavier targets. All the GEANT4 packages have the wrong slope for all targets and only agree in magnitude at lowest m_{t}.

Both FLUKA and GCALOR reproduce the slope of the K^{-} data reasonably well (Figure 10). The magnitude predicted by FLUKA is higher than the data, while GCALOR has better agreement. The slope of the Be data is reproduced reasonably well by the GEANT4 packages, but is lower in magnitude than the data. For the heavier targets, GEANT4 predicts a slope less than that of the data and agrees in magnitude only at lowest m_{t}.

The ratios of the Monte Carlo results to the data for proton production are shown in Figure 11. For the Be target, both FLUKA and the GEANT4 packages have a slope greater than that of the data with moderately good agreement with the data in magnitude at low m_{t}. For the heavier targets, FLUKA generally has good agreement for $y < 1.3$, but the predicted slope exceeds the data for larger rapidities. For the GEANT4 packages for the heavier targets, the agreement is poor for $y < 2.2$, 1.6, and 1.6 for Al, Cu, and Au, respectively, but improves somewhat at higher rapidities. In general the slope of the GEANT4 packages does not match the data well over the full range of measured m_{t}. It is notable that the greatest difference between QGSC and the other GEANT4 packages is for proton production and for the Au target. GCALOR has the poorest agreement with the data.

None of the simulation packages reproduces the deuteron data (Figure 6) well. Neither GCALOR nor FLUKA predict a significant production of deuterons for rapidity above 0.5. QGSC and QGSC_LEAD_HP underestimate the deuteron rate by an order of magnitude but do a reasonable job at predicting the slope of the deuteron data at low rapidity. The agreement is worse at rapidity greater than $\sim$0.8.

4 Conclusions and discussion

The FLUKA simulation package gives the best overall agreement with the E802 meson data with the greatest deviation between the data and Monte Carlo of a factor of ~ 2 over the entire kinematic range of the data. The agreement of the GEANT3 and GEANT4 packages was worse in general. The

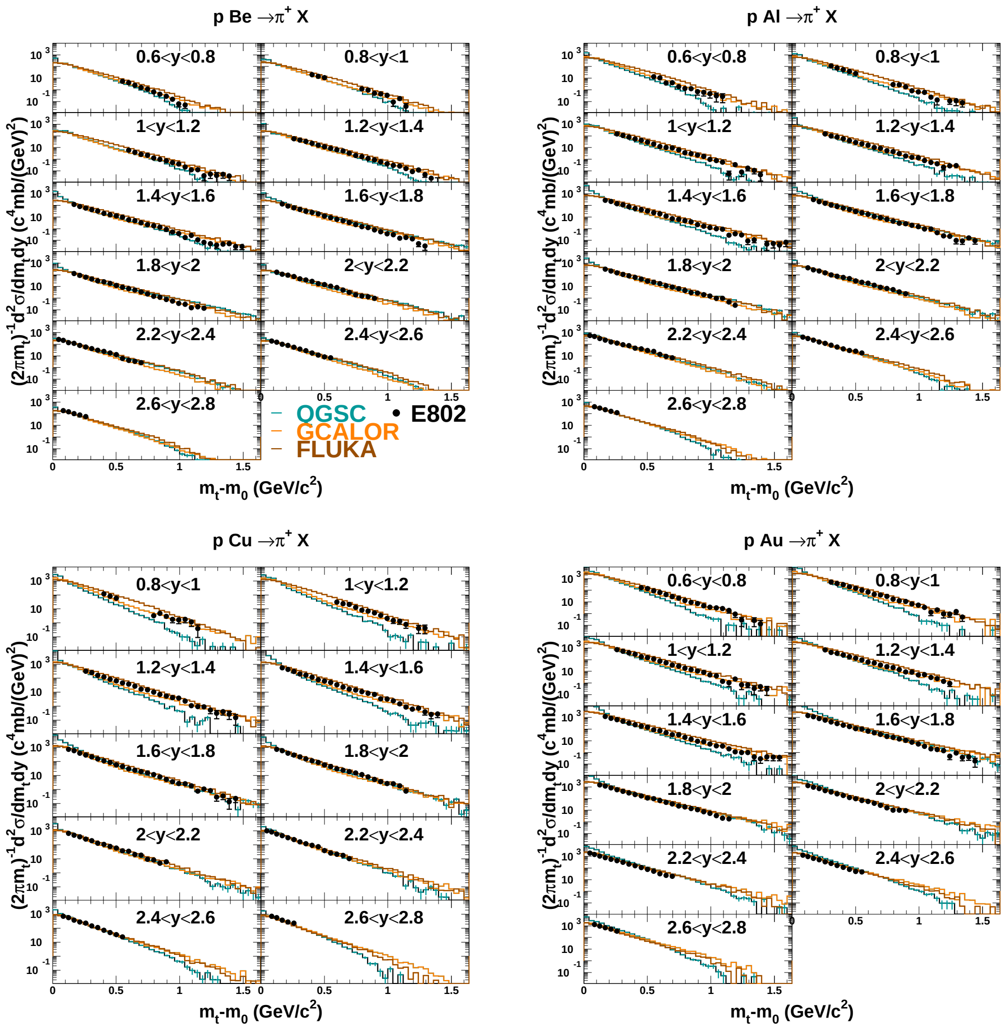

Fig. 1. The invariant cross section $\frac{d^2\sigma}{2\pi m_t dm_t dy}$ as a function of transverse kinetic energy $m_\mathrm{t} - m_0$ in 0.2 bins of rapidity compared to the simulation results for the π^+ data for p-Be, p-Al, p-Cu, and p-Au collisions. The statistical uncertainties for the different models is similar and is only shown for QGSC.

agreement of all the simulation packages with the proton and deuteron production data was less satisfactory than that for the meson data.

We note that a previous investigation with the JAM [9] simulation package gave good agreement and that JAM has been interfaced with GEANT4 [18] although there is no current plan to implement JAM as a hadronic physics list in GEANT4. In addition a great deal of data with similar targets and kinematics is currently being analyzed or accumulated [19] and should provide for validation and refinement of simulations.

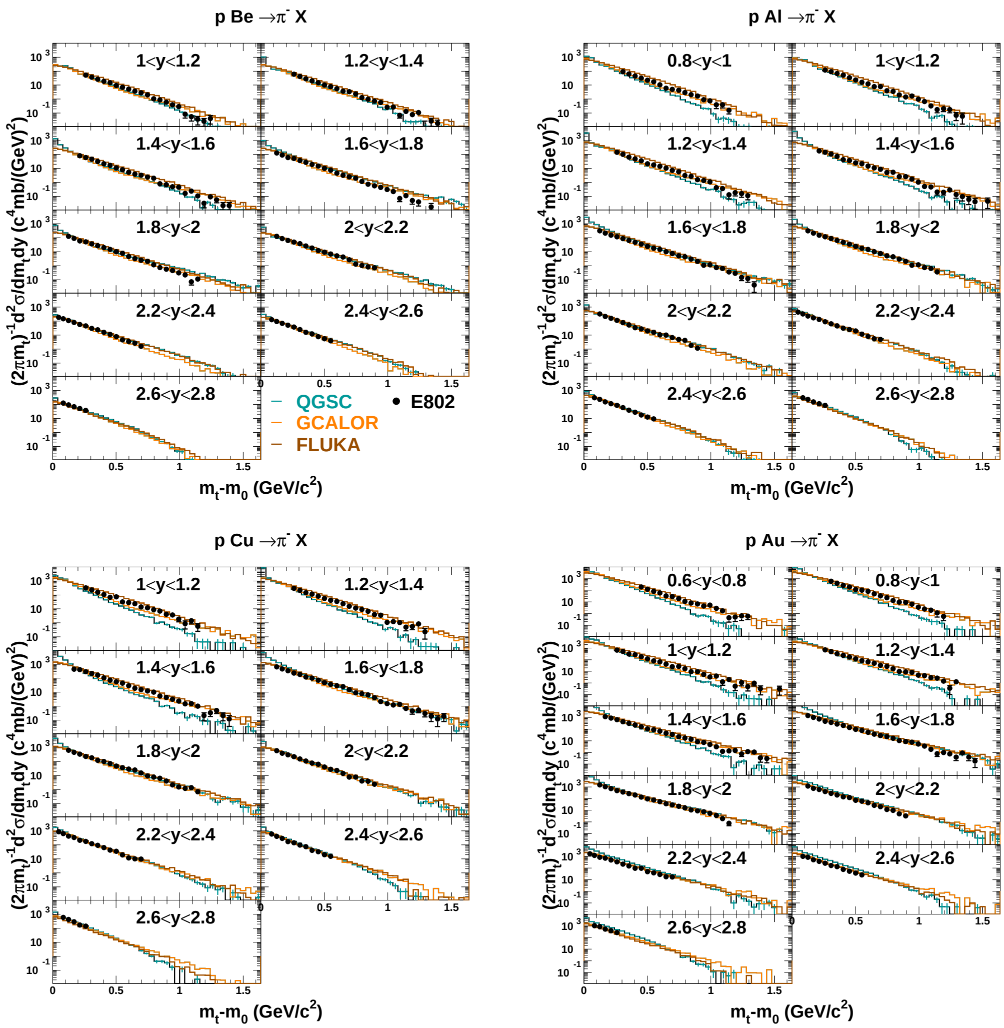

Fig. 2. The invariant cross section $\frac{d^2\sigma}{2\pi m_t dm_t dy}$ as a function of transverse kinetic energy $m_\mathrm{t} - m_0$ in 0.2 bins of rapidity compared to the simulation results for the π^- data for p-Be, p-Al, p-Cu, and p-Au collisions. The statistical uncertainties for the different models is similar and is only shown for QGSC.

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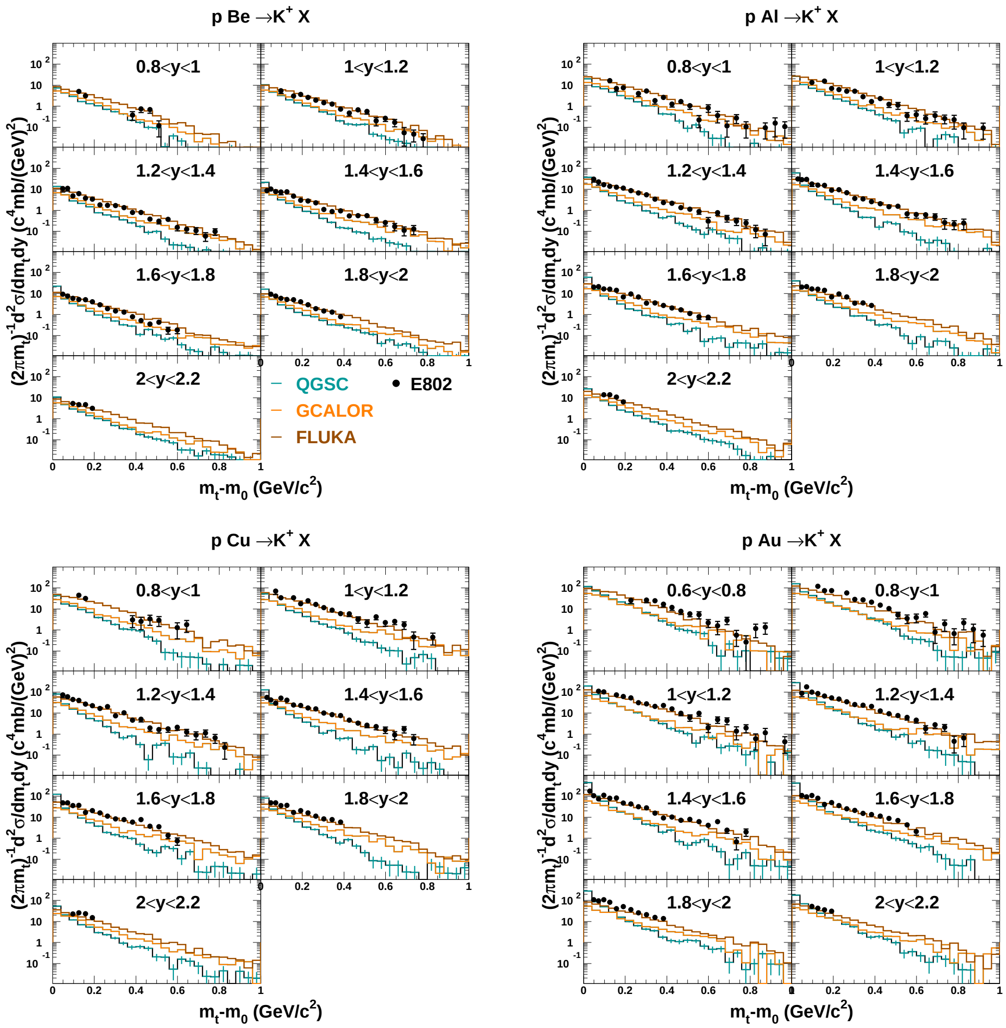

Fig. 3. The invariant cross section $\frac{d^2\sigma}{2\pi m_t dm_t dy}$ as a function of transverse kinetic energy $m_{\rm t} - m_0$ in 0.2 bins of rapidity compared to the simulation results for the K^+ data for p-Be, p-Al, p-Cu, and p-Au collisions. The statistical uncertainties for the different models is similar and is only shown for QGSC.

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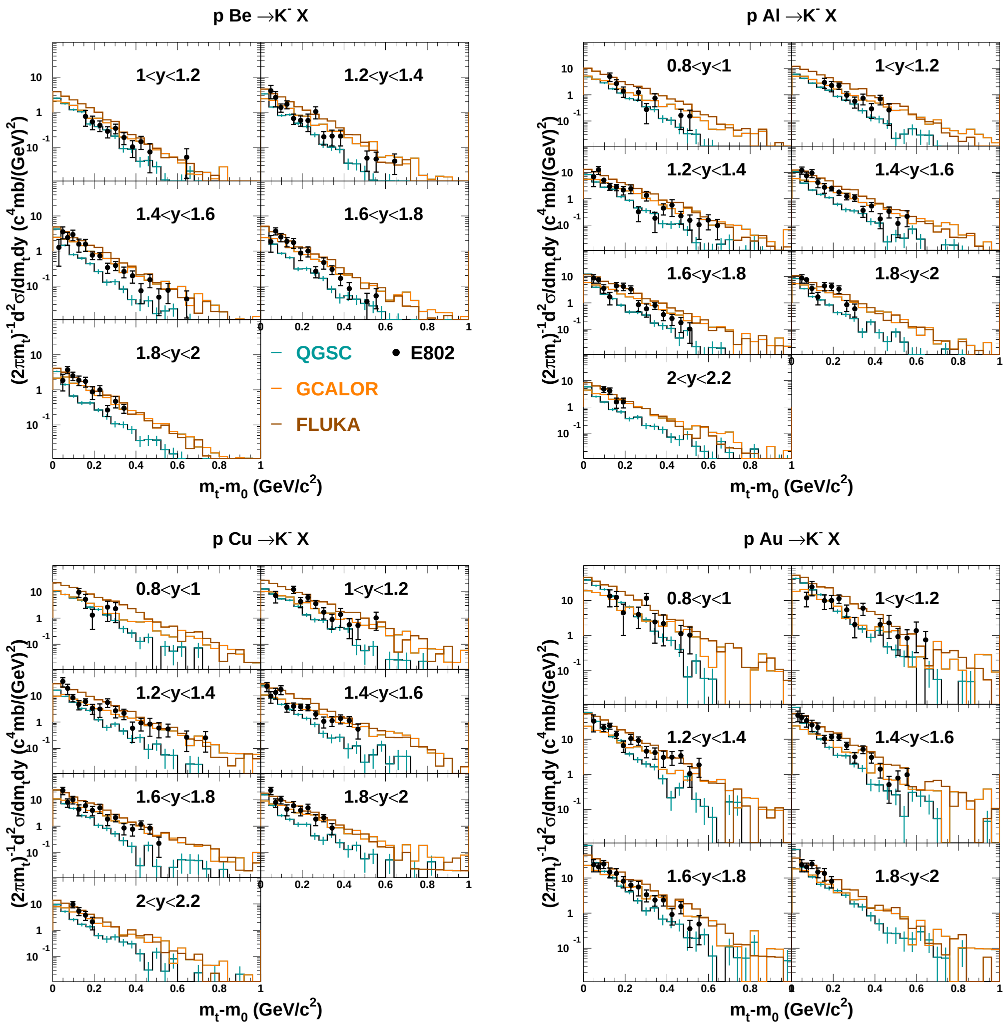

Fig. 4. The invariant cross section $\frac{d^2\sigma}{2\pi m_t dm_t dy}$ as a function of transverse kinetic energy $m_t - m_0$ in 0.2 bins of rapidity compared to the simulation results for the K^- data for p-Be, p-Al, p-Cu, and p-Au collisions. The statistical uncertainties for the different models is similar and is only shown for QGSC.

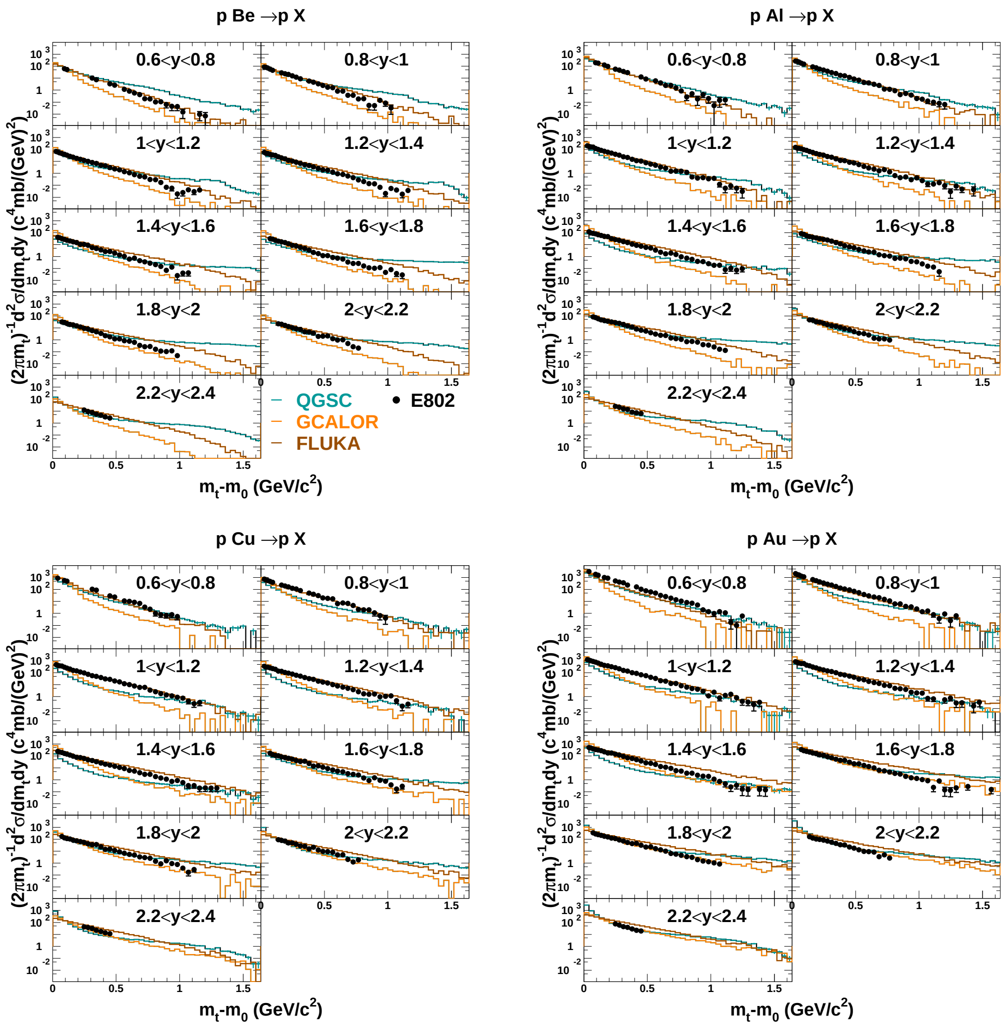

Fig. 5. The invariant cross section $\frac{d^2\sigma}{2\pi m_t dm_t dy}$ as a function of transverse kinetic energy $m_t - m_0$ in 0.2 bins of rapidity compared to the simulation results for the proton data for p-Be, p-Al, p-Cu, and p-Au collisions. The statistical uncertainties for the different models is similar and is only shown for QGSC.

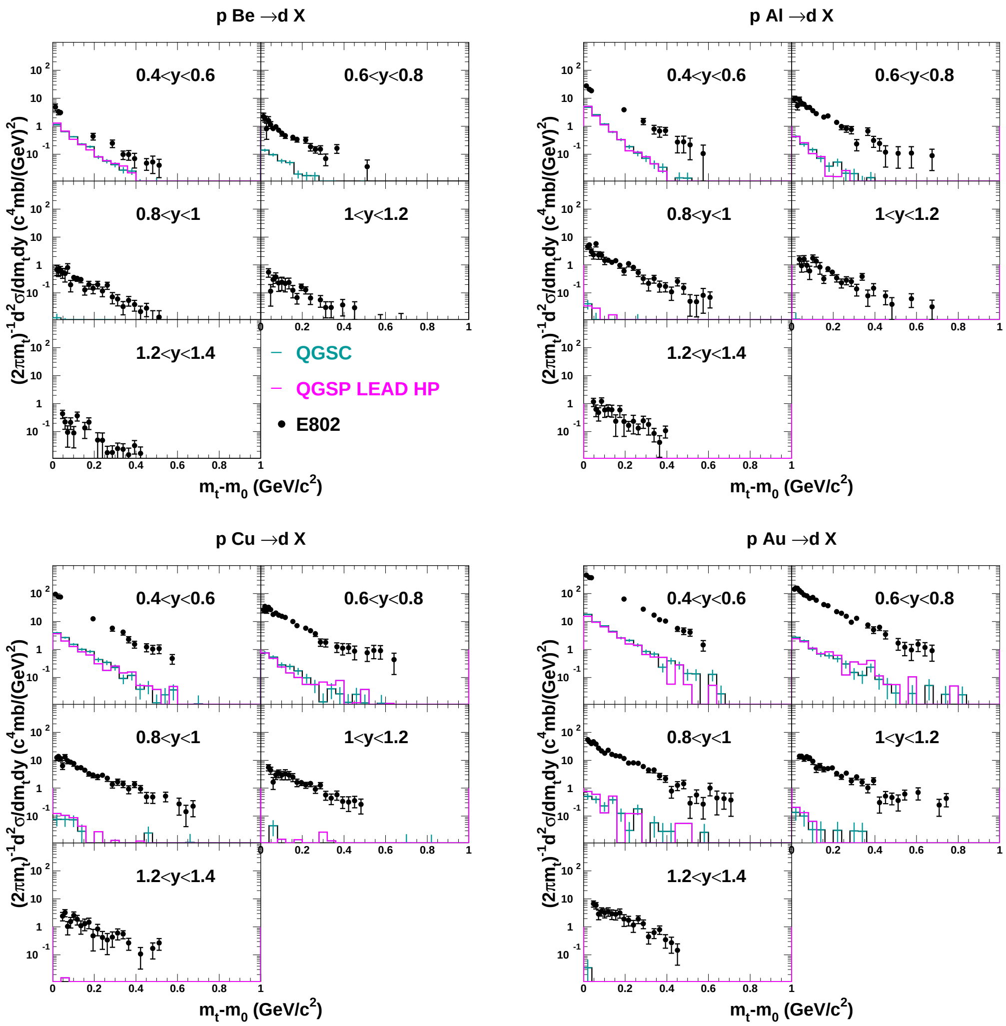

Fig. 6. The invariant cross section $\frac{d^2\sigma}{2\pi m_t dm_t dy}$ as a function of transverse kinetic energy $m_t - m_0$ in 0.2 bins of rapidity compared to the simulation results for the deuteron data for p-Be, p-Al, p-Cu, and p-Au collisions. The statistical uncertainties for the different models is similar and is only shown for QGSC.

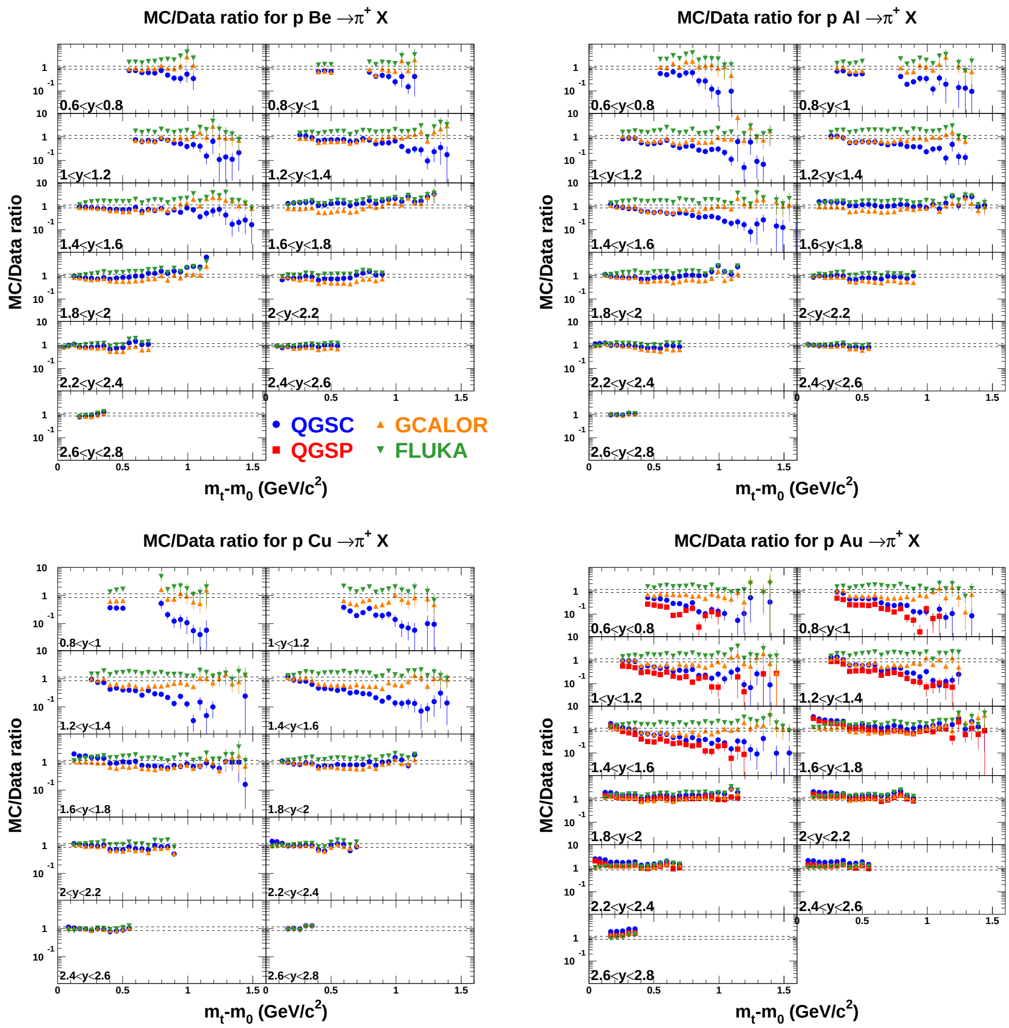

Fig. 7. The ratio of the simulated (MC) and data invariant cross sections as a function of transverse kinetic energy $m_t - m_0$ in 0.2 bins of rapidity for the π^+ data for p-Be, p-Al, p-Cu, and p-Au collisions. The horizontal dashed lines indicate the $\pm15\%$ normalization uncertainty of the E802 data. Only the QGSC ratios are shown as all the GEANT4 models given consistent predictions except for the gold target.

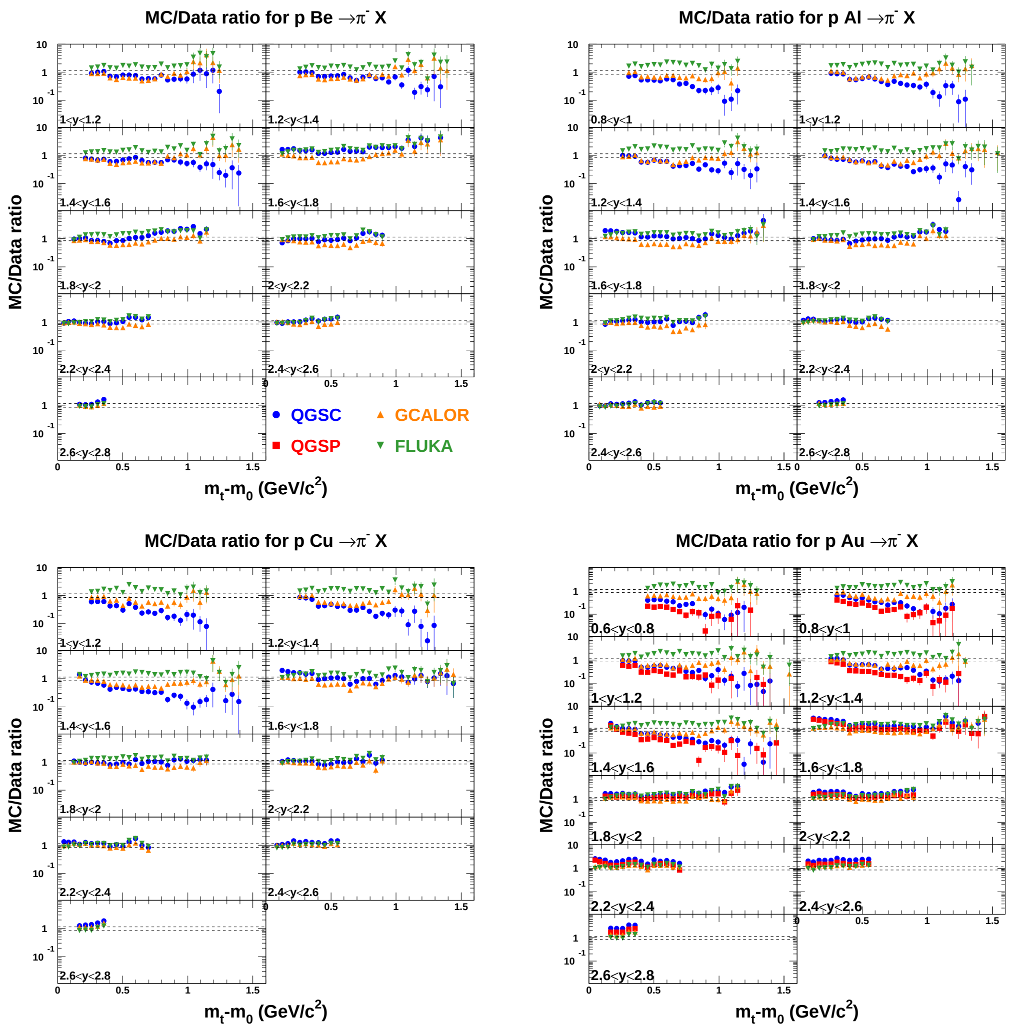

Fig. 8. The ratio of the simulated (MC) and data invariant cross sections as a function of transverse kinetic energy $m_\mathrm{t} - m_0$ in 0.2 bins of rapidity for the π^- data for p-Be, p-Al, p-Cu, and p-Au collisions. The horizontal dashed lines indicate the $\pm 15\%$ normalization uncertainty of the E802 data. Only the QGSC ratios are shown as all the GEANT4 models given consistent predictions except for the gold target.

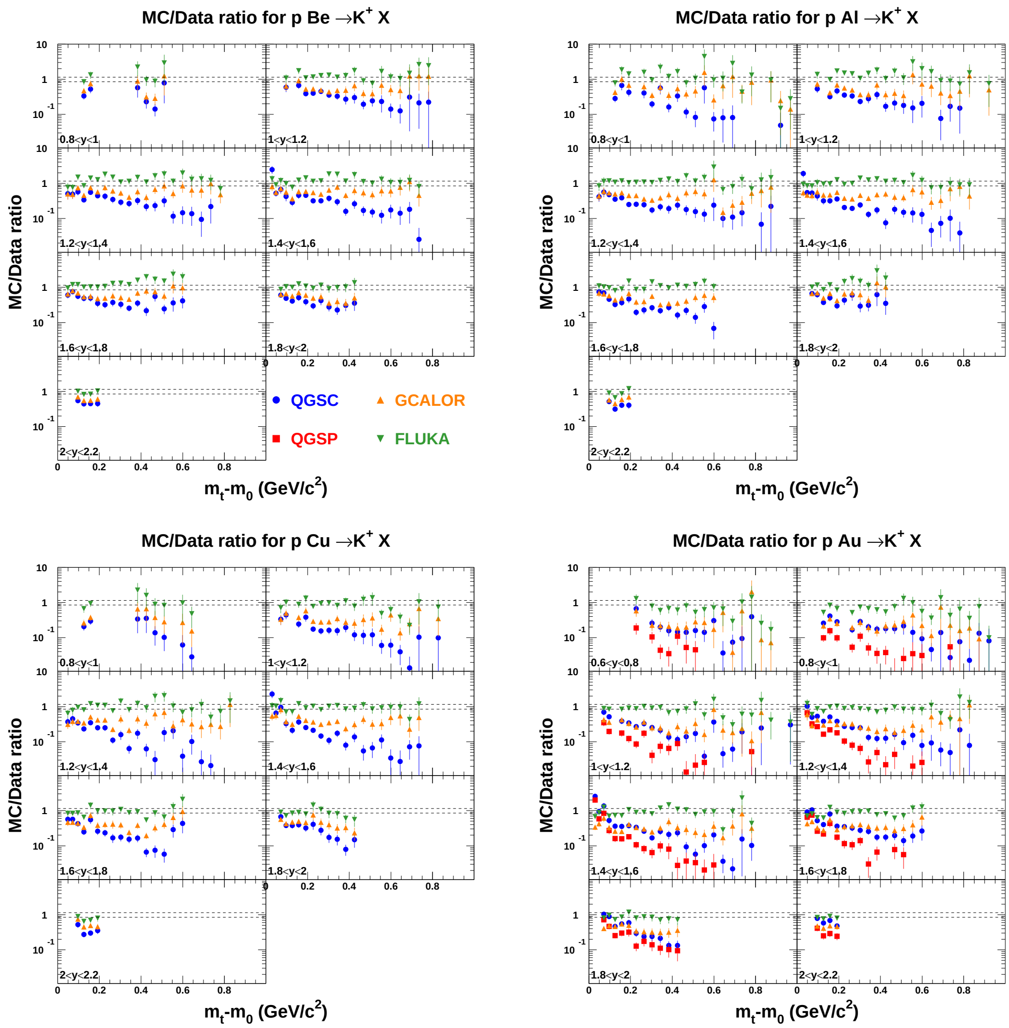

Fig. 9. The ratio of the simulated (MC) and data invariant cross sections as a function of transverse kinetic energy $m_{\mathrm{t}} - m_0$ in 0.2 bins of rapidity for the K^+ data for p-Be, p-Al, p-Cu, and p-Au collisions. The horizontal dashed lines indicate the $\pm 15\%$ normalization uncertainty of the E802 data. Only the QGSC ratios are shown as all the GEANT4 models given consistent predictions except for the gold target.

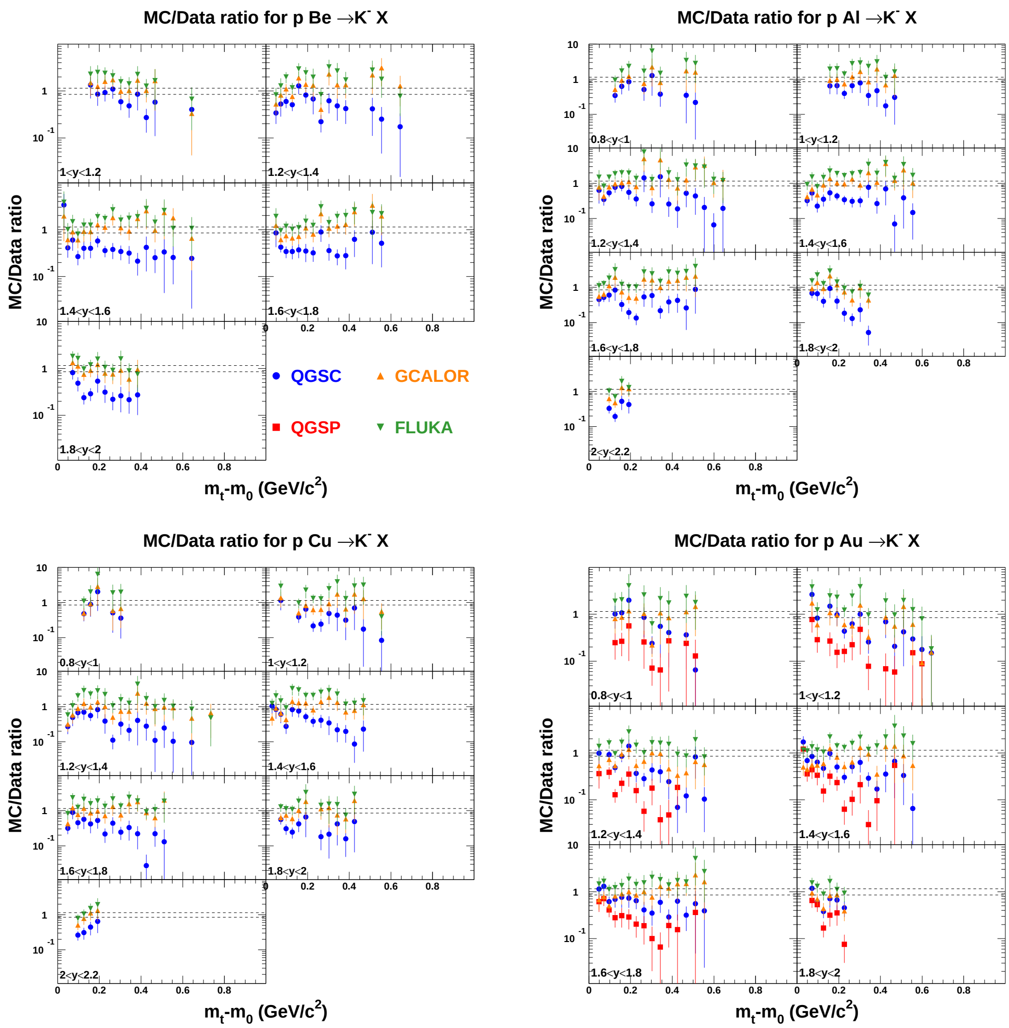

Fig. 10. The ratio of the simulated (MC) and data invariant cross sections as a function of transverse kinetic energy $m_t - m_0$ in 0.2 bins of rapidity for the K^- data for p-Be, p-Al, p-Cu, and p-Au collisions. The horizontal dashed lines indicate the $\pm 15\%$ normalization uncertainty of the E802 data. Only the QGSC ratios are shown as all the GEANT4 models given consistent predictions except for the gold target.

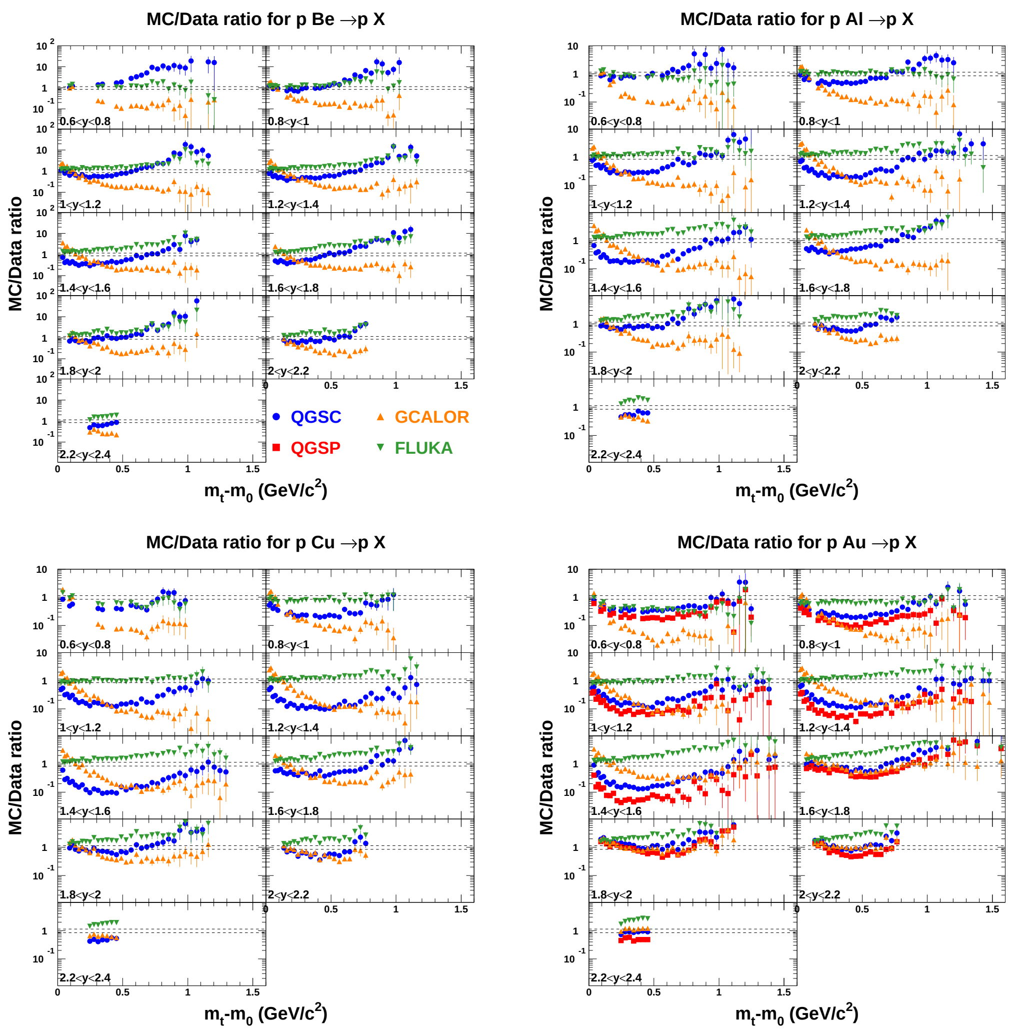

Fig. 11. The ratio of the simulated (MC) and data invariant cross sections as a function of transverse kinetic energy $m_{\rm t} - m_0$ in 0.2 bins of rapidity for the proton data for p-Be, p-Al, p-Cu, and p-Au collisions. The horizontal dashed lines indicate the $\pm15\%$ normalization uncertainty of the E802 data. Only the QGSC ratios are shown as all the GEANT4 models given consistent predictions except for the gold target. Note that the vertical upper limit for the p-Be ratios are an order of magnitude larger than the other targets.

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